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(54) **THREADING AS A SERVICE**

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G06F 9/455	(2006.01)

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CPC ***G06F 9/45533*** (2013.01); ***G06F 9/50*** (2013.01); *G06F 2009/4557* (2013.01); *G06F 2009/45562* (2013.01)

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CPC G06F 9/45533; G06F 9/5077; G06F 9/45558; G06F 2009/4557; G06F 2009/45562; G06F 9/5072; G06F 21/53
See application file for complete search history.

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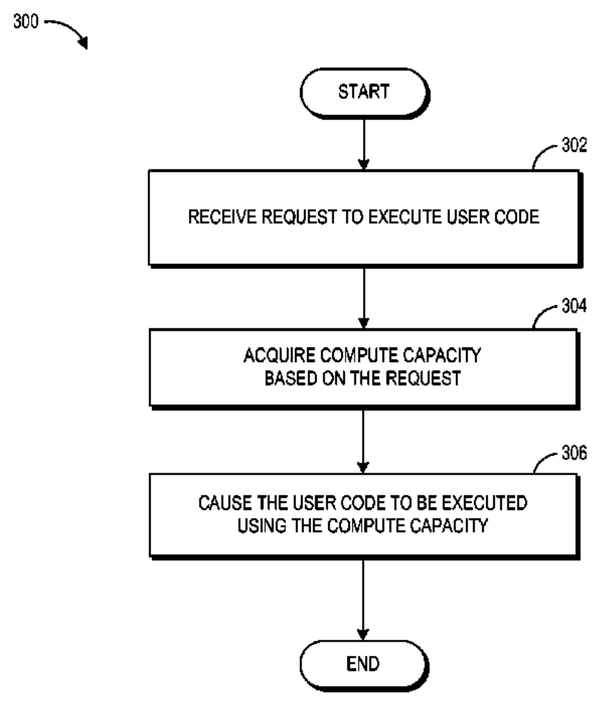
(57) **ABSTRACT**

A service manages a plurality of virtual machine instances for low latency execution of user codes. The plurality of virtual machine instances can be configured based on a predetermined set of configurations. One or more containers may be created within the virtual machine instances. In response to a request to execute user code, the service identifies a pre-configured virtual machine instance suitable for executing the user code. The service can allocate the identified virtual machine instance to the user, create a new container within an instance already allocated to the user, or re-use a container already created for execution of the user code. When the user code has not been activated for a time-out period, the service can invalidate allocation of the virtual machine instance destroy the container. The time from receiving the request to beginning code execution is less than a predetermined duration, for example, 100 ms.

34 Claims, 4 Drawing Sheets



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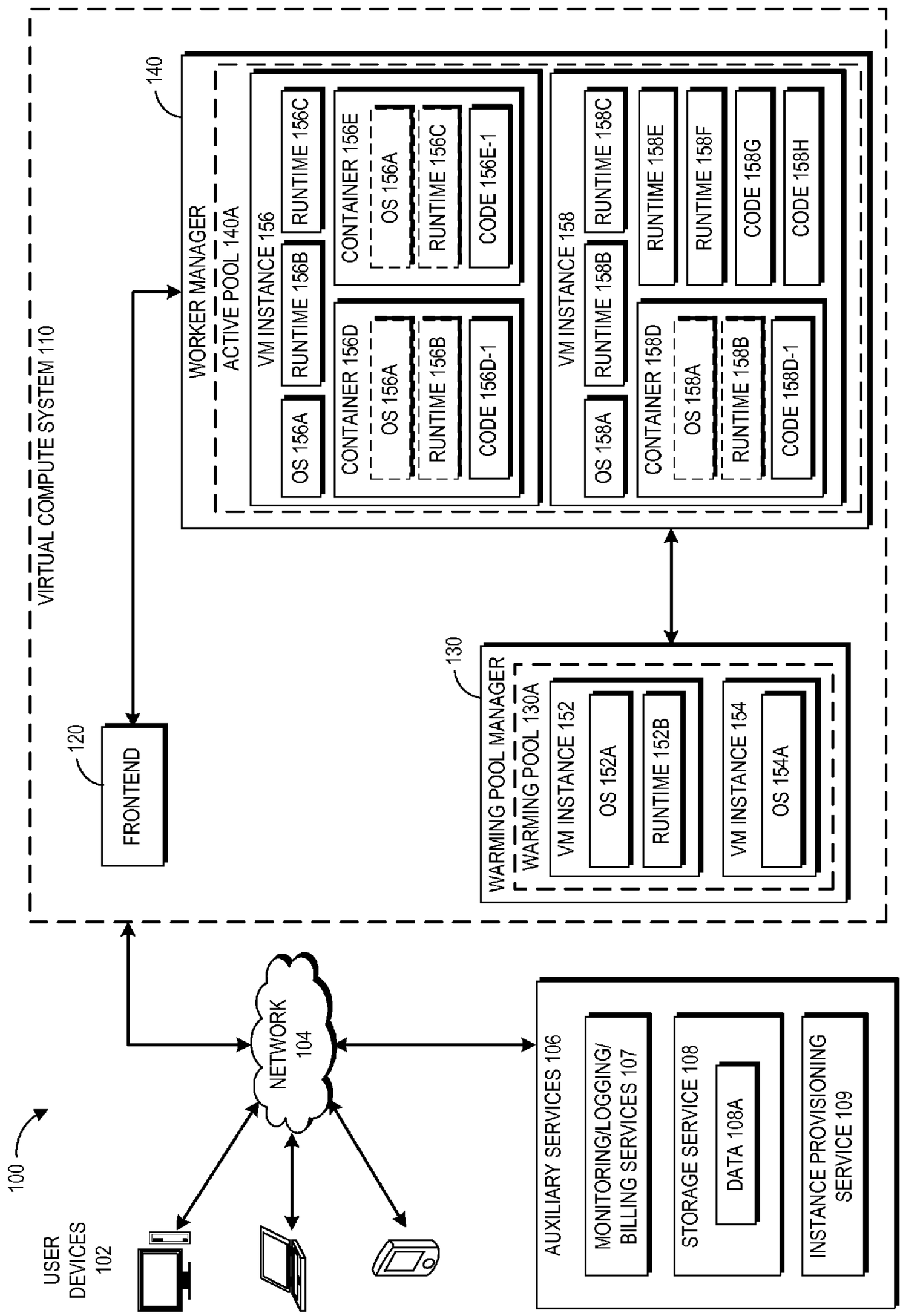
USER DEVICES 102
100
NETWORK 104
AUXILIARY SERVICES 106
MONITORING/LOGGING/ BILLING SERVICES 107
STORAGE SERVICE 108
DATA 108A
INSTANCE PROVISIONING SERVICE 109
VIRTUAL COMPUTE SYSTEM 110
FRONTEND
120
WARMING POOL MANAGER
130
WARMING POOL 130A
VM INSTANCE 152
OS 152A
RUNTIME 152B
VM INSTANCE 154
OS 154A
WORKER MANAGER
140
ACTIVE POOL 140A
VM INSTANCE 156
OS 156A
RUNTIME 156B
RUNTIME 156C
CONTAINER 156D
OS 156A
RUNTIME 156B
CODE 156D-1
CONTAINER 156E
OS 156A
RUNTIME 156C
CODE 156E-1
VM INSTANCE 158
OS 158A
RUNTIME 158B
RUNTIME 158C
CONTAINER 158D
OS 158A
RUNTIME 158B
CODE 158D-1
RUNTIME 158E
RUNTIME 158F
CODE 158G
CODE 158H

FIG. 1

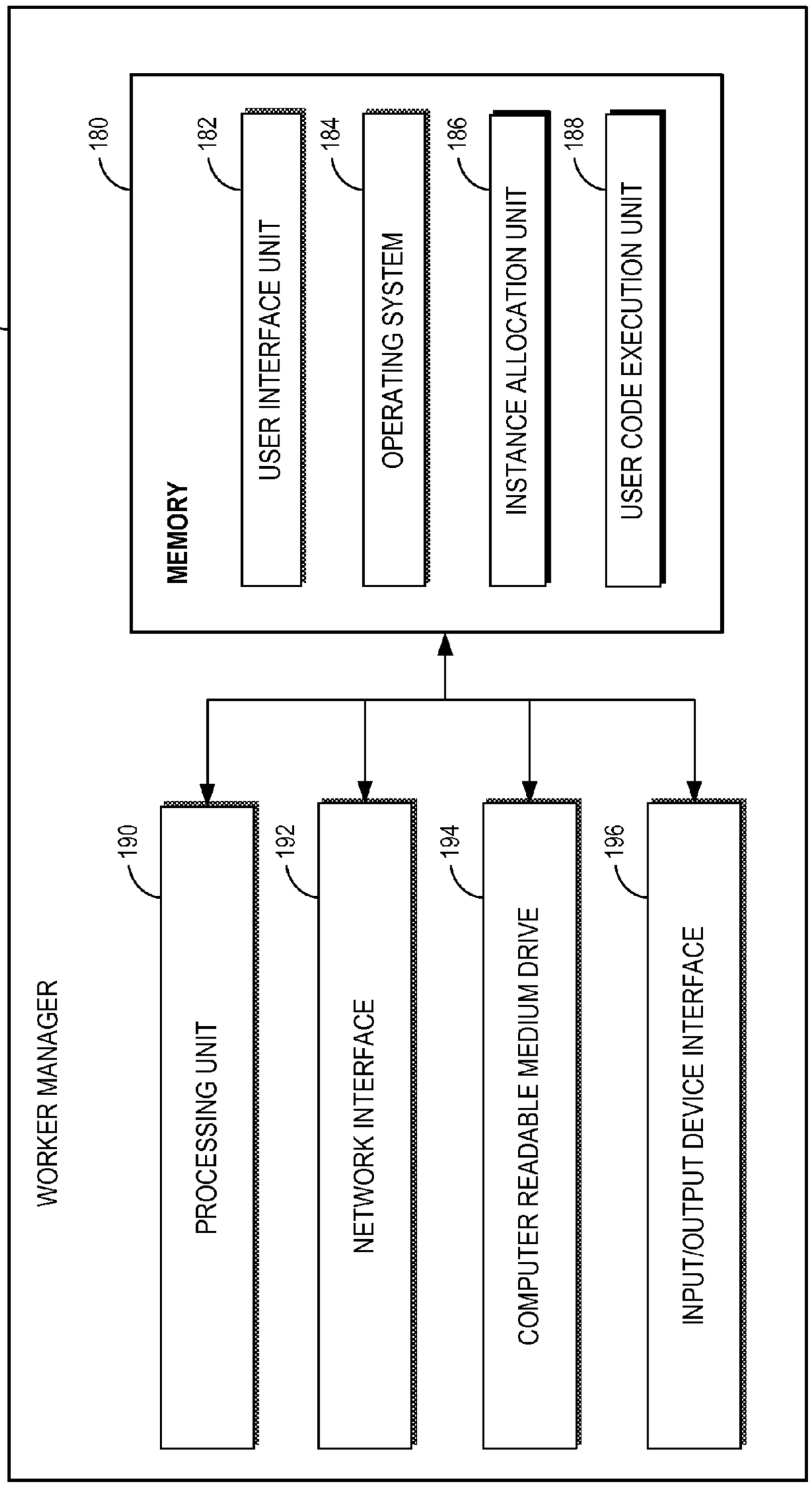
140
WORKER MANAGER
180
MEMORY
182
USER INTERFACE UNIT
184
OPERATING SYSTEM
186
INSTANCE ALLOCATION UNIT
188
USER CODE EXECUTION UNIT
190
PROCESSING UNIT
192
NETWORK INTERFACE
194
COMPUTER READABLE MEDIUM DRIVE
196
INPUT/OUTPUT DEVICE INTERFACE

FIG. 2

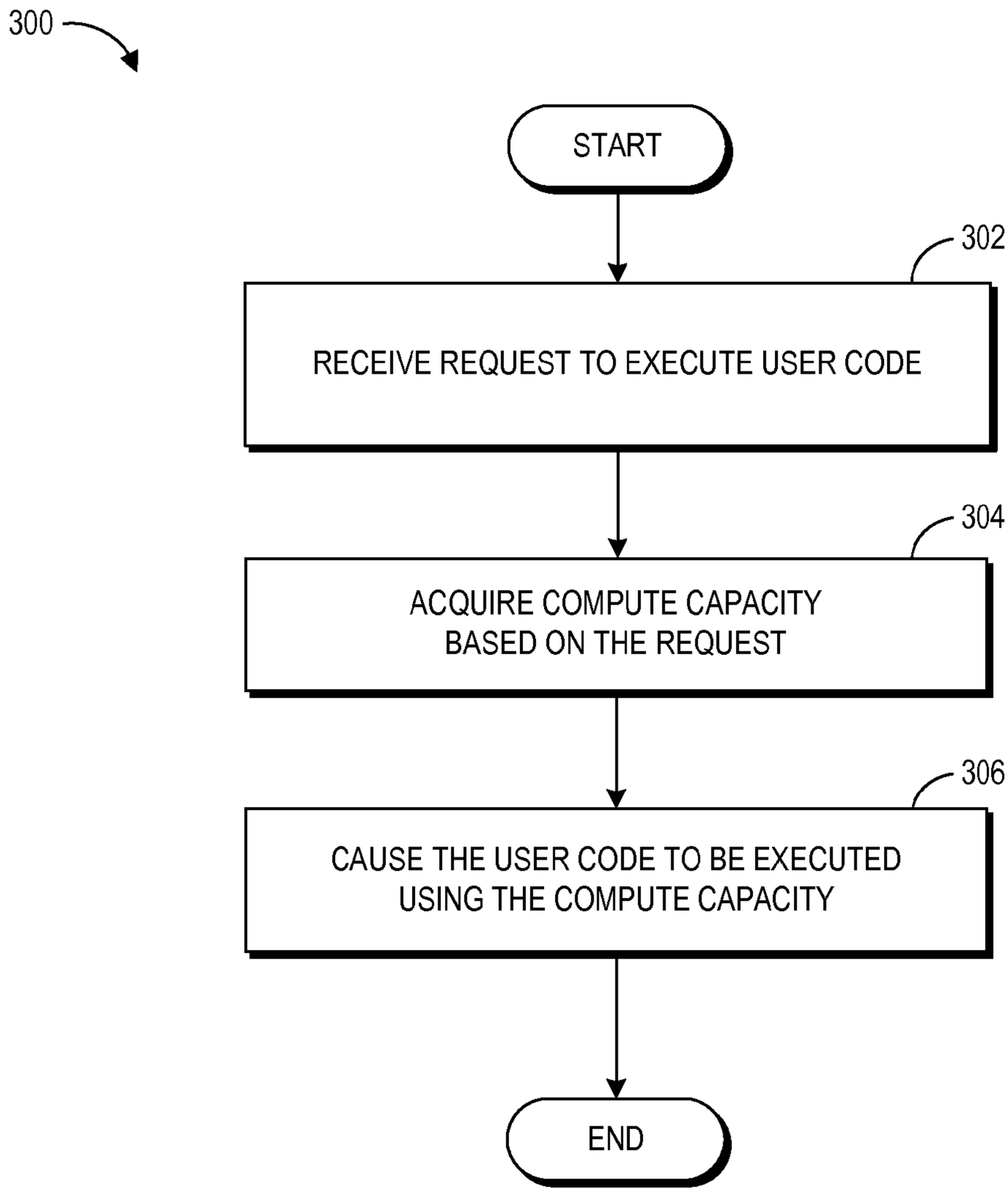
300
START
302
RECEIVE REQUEST TO EXECUTE USER CODE
304
ACQUIRE COMPUTE CAPACITY
BASED ON THE REQUEST
306
CAUSE THE USER CODE TO BE EXECUTED
USING THE COMPUTE CAPACITY
END

FIG. 3

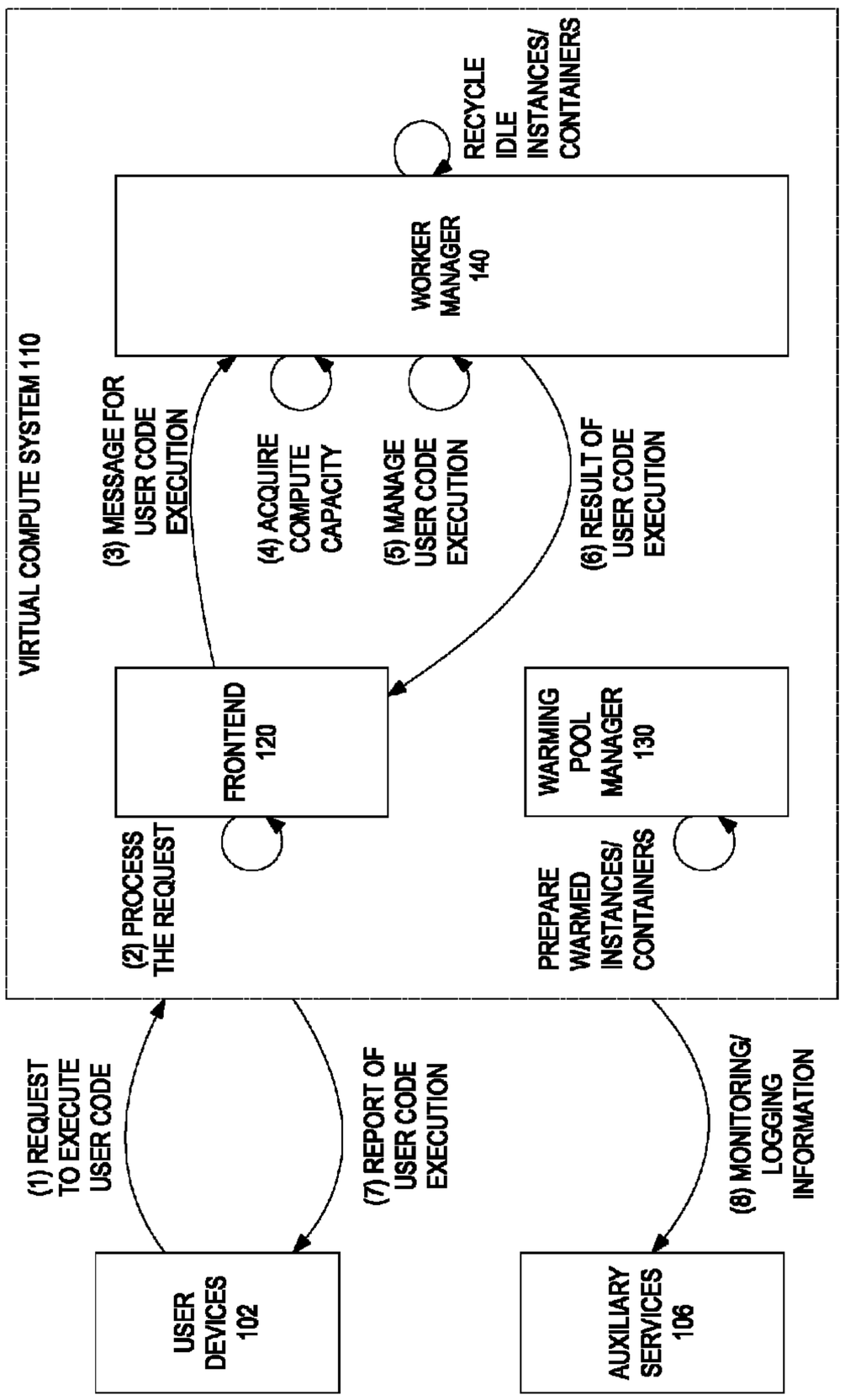
VIRTUAL COMPUTE SYSTEM 110
RECYCLE IDLE INSTANCES/ CONTAINERS
WORKER MANAGER 140
(3) MESSAGE FOR USER CODE EXECUTION
(4) ACQUIRE COMPUTE CAPACITY
(5) MANAGE USER CODE EXECUTION
(6) RESULT OF USER CODE EXECUTION
FRONTEND 120
WARMING POOL MANAGER 130
(2) PROCESS THE REQUEST
PREPARE WARMED INSTANCES/ CONTAINERS
(1) REQUEST TO EXECUTE USER CODE
(7) REPORT OF USER CODE EXECUTION
(8) MONITORING/ LOGGING INFORMATION
USER DEVICES 102
AUXILIARY SERVICES 106

FIG. 4

THREADING AS A SERVICE

CROSS-REFERENCE TO CONCURRENTLY-FILED APPLICATIONS

The present application's Applicant is concurrently filing the following U.S. patent applications on Sep. 30, 2014:

	Title
14/502,589	MESSAGE-BASED COMPUTATION REQUEST SCHEDULING
14/502,810	LOW LATENCY COMPUTATIONAL CAPACITY PROVISIONING
14/502,714	AUTOMATIC MANAGEMENT OF LOW LATENCY COMPUTATIONAL CAPACITY
14/502,648	PROGRAMMATIC EVENT DETECTION AND MESSAGE GENERATION FOR REQUESTS TO EXECUTE PROGRAM CODE
14/502,741	PROCESSING EVENT MESSAGES FOR USER REQUESTS TO EXECUTE PROGRAM CODE
14/502,620	DYNAMIC CODE DEPLOYMENT AND VERSIONING

The disclosures of the above-referenced applications are hereby incorporated by reference in their entireties.

BACKGROUND

Generally described, computing devices utilize a communication network, or a series of communication networks, to exchange data. Companies and organizations operate computer networks that interconnect a number of computing devices to support operations or to provide services to third parties. The computing systems can be located in a single geographic location or located in multiple, distinct geographic locations (e.g., interconnected via private or public communication networks). Specifically, data centers or data processing centers, herein generally referred to as a "data center," may include a number of interconnected computing systems to provide computing resources to users of the data center. The data centers may be private data centers operated on behalf of an organization or public data centers operated on behalf, or for the benefit of, the general public.

To facilitate increased utilization of data center resources, virtualization technologies may allow a single physical computing device to host one or more instances of virtual machines that appear and operate as independent computing devices to users of a data center. With virtualization, the single physical computing device can create, maintain, delete, or otherwise manage virtual machines in a dynamic manner. In turn, users can request computer resources from a data center, including single computing devices or a configuration of networked computing devices, and be provided with varying numbers of virtual machine resources.

In some scenarios, virtual machine instances may be configured according to a number of virtual machine instance types to provide specific functionality. For example, various computing devices may be associated with different combinations of operating systems or operating system configurations, virtualized hardware resources and software applications to enable a computing device to provide different desired functionalities, or to provide similar functionalities more efficiently. These virtual machine instance type configurations are often contained within a device image, which includes static data containing the software (e.g., the OS and applications together with their configuration and data files, etc.) that the virtual machine will run once started.

The device image is typically stored on the disk used to create or initialize the instance. Thus, a computing device may process the device image in order to implement the desired software configuration.

BRIEF DESCRIPTION OF DRAWINGS

The foregoing aspects and many of the attendant advantages of this disclosure will become more readily appreciated as the same become better understood by reference to the following detailed description, when taken in conjunction with the accompanying drawings, wherein:

FIG. **1** is a block diagram depicting an illustrative environment for acquiring low latency compute capacity;

FIG. **2** depicts a general architecture of a computing device providing a virtual compute system manager for acquiring low latency compute capacity;

FIG. **3** is a flow diagram illustrating a low latency compute capacity acquisition routine implemented by a worker manager, according to an example aspect; and

FIG. **4** is a block diagram illustrating processes of virtual machine instance management to process a request to execute user code.

DETAILED DESCRIPTION

Companies and organizations no longer need to acquire and manage their own data centers in order to perform computing operations (e.g., execute code, including threads, programs, software, routines, subroutines, processes, etc.). With the advent of cloud computing, storage space and compute power traditionally provided by hardware computing devices can now be obtained and configured in minutes over the Internet. Thus, developers can quickly purchase a desired amount of computing resources without having to worry about acquiring physical machines. Such computing resources are typically purchased in the form of virtual computing resources, or virtual machine instances. These instances of virtual machines, which are hosted on physical computing devices with their own operating systems and other software components, can be utilized in the same manner as physical computers.

However, even when virtual computing resources are purchased, developers still have to decide how many and what type of virtual machine instances to purchase, and how long to keep them. For example, the costs of using the virtual machine instances may vary depending on the type and the number of hours they are rented. In addition, the minimum time a virtual machine may be rented is typically on the order of hours. Further, developers have to specify the hardware and software resources (e.g., type of operating systems and language runtimes, etc.) to install on the virtual machines. Other concerns that they might have include over-utilization (e.g., acquiring too little computing resources and suffering performance issues), under-utilization (e.g., acquiring more computing resources than necessary to run the codes, and thus overpaying), prediction of change in traffic (e.g., so that they know when to scale up or down), and instance and language runtime startup delay, which can take 3-10 minutes, or longer, even though users may desire computing capacity on the order of seconds or even milliseconds. Thus, an improved method of allowing users to take advantage of the virtual machine instances provided by service providers is desired.

According to aspects of the present disclosure, by maintaining a pool of pre-initialized virtual machine instances that are ready for use as soon as a user request is received,

delay (sometimes referred to as latency) associated with executing the user code (e.g., instance and language runtime startup time) can be significantly reduced.

Generally described, aspects of the present disclosure relate to the management of virtual machine instances and containers created therein. Specifically, systems and methods are disclosed which facilitate management of virtual machine instances in a virtual compute system. The virtual compute system maintains a pool of virtual machine instances that have one or more software components (e.g., operating systems, language runtimes, libraries, etc.) loaded thereon. The virtual machine instances in the pool can be designated to service user requests to execute program codes. The program codes can be executed in isolated containers that are created on the virtual machine instances. Since the virtual machine instances in the pool have already been booted and loaded with particular operating systems and language runtimes by the time the requests are received, the delay associated with finding compute capacity that can handle the requests (e.g., by executing the user code in one or more containers created on the virtual machine instances) is significantly reduced.

In another aspect, a virtual compute system may maintain a pool of virtual machine instances on one or more physical computing devices, where each virtual machine instance has one or more software components loaded thereon. When the virtual compute system receives a request to execute the program code of a user, which specifies one or more computing constraints for executing the program code of the user, the virtual compute system may select a virtual machine instance for executing the program code of the user based on the one or more computing constraints specified by the request and cause the program code of the user to be executed on the selected virtual machine instance.

Generally described, aspects of the present disclosure relate to management of virtual machine instances to enable threading as a service. Specifically, systems and methods are disclosed which facilitate the management of virtual machine instance through utilization of a virtual machine instance manager, such that a service can receive user code (threads, programs, etc.) and execute the code in a highly scalable, low latency manner, without requiring user configuration of a virtual machine instance. The virtual machine instance manager manages virtual machine instances that can execute user code composed in any of a variety of programming languages. The virtual machine instance manager can create and configure virtual machine instances according to a predetermined set of configurations prior to receiving the user code and prior to receiving any information from a user regarding any particular virtual machine instance configuration. Instead, the virtual machine instance manager can pre-configure and establish a variety of virtual machine instances, each having a configuration corresponding to any one or more of a variety of run-time environments. In response to a request to execute user code, the virtual machine instance manager can identify a pre-configured virtual machine instance based on configuration information associated with the request and allocate the identified virtual machine instance to execute the user's code. The virtual machine instance manager can create and configure containers inside the allocated virtual machine instance based on configuration information of the request to execute the user code. In some cases, the virtual machine instance manager can identify an existing container in a virtual machine instance that is already allocated to the same user account. Containers within a single virtual machine instance can host multiple copies of the same user code concurrently and also can host copies of different user codes if allowed under operation policies. In some cases, the virtual machine instance manager manages and facilitates execution of the requested user code by the containers by utilizing various auxiliary services.

Specific embodiments and example applications of the present disclosure will now be described with reference to the drawings. These embodiments and example applications are intended to illustrate, and not limit, the present disclosure.

By way of illustration, various example user computing devices **102** are shown in communication with the virtual compute system **110**, including a desktop computer, laptop, and a mobile phone. In general, the user computing devices **102** can be any computing device such as a desktop, laptop, mobile phone (or smartphone), tablet, kiosk, wireless device, and other electronic devices. In addition, the user computing devices **102** may include web services running on the same or different data centers, where, for example, different web services may programmatically communicate with each other to perform one or more techniques described herein. Further, the user computing devices **102** may include Internet of Things (IoT) devices such as Internet appliances and connected devices. The virtual compute system **110** may provide the user computing devices **102** with one or more user interfaces, command-line interfaces (CLI), application programming interfaces (API), and/or other programmatic interfaces for generating and uploading user codes, invoking the user codes (e.g., submitting a request to execute the user codes on the virtual compute system **110**), scheduling event-based jobs or timed jobs, tracking the user codes, and/or viewing other logging or monitoring information related to their requests and/or user codes. Although one or more embodiments may be described herein as using a user interface, it should be appreciated that such embodiments may, additionally or alternatively, use any CLIs, APIs, or other programmatic interfaces.

The user computing devices **102** access the virtual compute system **110** over a network **104**. The network **104** may be any wired network, wireless network, or combination thereof. In addition, the network **104** may be a personal area network, local area network, wide area network, over-the-air broadcast network (e.g., for radio or television), cable network, satellite network, cellular telephone network, or combination thereof. For example, the network **104** may be a publicly accessible network of linked networks, possibly operated by various distinct parties, such as the Internet. In some embodiments, the network **104** may be a private or semi-private network, such as a corporate or university intranet. The network **104** may include one or more wireless networks, such as a Global System for Mobile Communications (GSM) network, a Code Division Multiple Access (CDMA) network, a Long Term Evolution (LTE) network, or any other type of wireless network. The network **104** can use protocols and components for communicating via the Internet or any of the other aforementioned types of networks. For example, the protocols used by the network **104** may include Hypertext Transfer Protocol (HTTP), HTTP Secure (HTTPS), Message Queue Telemetry Transport (MQTT), Constrained Application Protocol (CoAP), and the like. Protocols and components for communicating via the Internet or any of the other aforementioned types of communication networks are well known to those skilled in the art and, thus, are not described in more detail herein.

The virtual compute system **110** is depicted in FIG. **1** as operating in a distributed computing environment including several computer systems that are interconnected using one

or more computer networks. The virtual compute system **110** could also operate within a computing environment having a fewer or greater number of devices than are illustrated in FIG. **1**. Thus, the depiction of the virtual compute system **110** in FIG. **1** should be taken as illustrative and not limiting to the present disclosure. For example, the virtual compute system **110** or various constituents thereof could implement various Web services components, hosted or "cloud" computing environments, and/or peer to peer network configurations to implement at least a portion of the processes described herein.

Further, the virtual compute system **110** may be implemented in hardware and/or software and may, for instance, include one or more physical or virtual servers implemented on physical computer hardware configured to execute computer executable instructions for performing various features that will be described herein. The one or more servers may be geographically dispersed or geographically co-located, for instance, in one or more data centers.

In the environment illustrated FIG. **1**, the virtual environment **100** includes a virtual compute system **110**, which includes a frontend **120**, a warming pool manager **130**, and a worker manager **140**. In the depicted example, virtual machine instances ("instances") **152**, **154** are shown in a warming pool **130**A managed by the warming pool manager **130**, and instances **156**, **158** are shown in an active pool **140**A managed by the worker manager **140**. The illustration of the various components within the virtual compute system **110** is logical in nature and one or more of the components can be implemented by a single computing device or multiple computing devices. For example, the instances **152**, **154**, **156**, **158** can be implemented on one or more physical computing devices in different various geographic regions. Similarly, each of the frontend **120**, the warming pool manager **130**, and the worker manager **140** can be implemented across multiple physical computing devices. Alternatively, one or more of the frontend **120**, the warming pool manager **130**, and the worker manager **140** can be implemented on a single physical computing device. In some embodiments, the virtual compute system **110** may comprise multiple frontends, multiple warming pool managers, and/or multiple worker managers. Although four virtual machine instances are shown in the example of FIG. **1**, the embodiments described herein are not limited as such, and one skilled in the art will appreciate that the virtual compute system **110** may comprise any number of virtual machine instances implemented using any number of physical computing devices. Similarly, although a single warming pool and a single active pool are shown in the example of FIG. **1**, the embodiments described herein are not limited as such, and one skilled in the art will appreciate that the virtual compute system **110** may comprise any number of warming pools and active pools.

In the example of FIG. **1**, the virtual compute system **110** is illustrated as connected to the network **104**. In some embodiments, any of the components within the virtual compute system **110** can communicate with other components (e.g., the user computing devices **102** and auxiliary services **106**, which may include monitoring/logging/billing services **107**, storage service **108**, an instance provisioning service **109**, and/or other services that may communicate with the virtual compute system **110**) of the virtual environment **100** via the network **104**. In other embodiments, not all components of the virtual compute system **110** are capable of communicating with other components of the virtual environment **100**. In one example, only the frontend **120** may be connected to the network **104**, and other components of the virtual compute system **110** may communicate with other components of the virtual environment **100** via the frontend **120**.

Users may use the virtual compute system **110** to execute user code thereon. For example, a user may wish to run a piece of code in connection with a web or mobile application that the user has developed. One way of running the code would be to acquire virtual machine instances from service providers who provide infrastructure as a service, configure the virtual machine instances to suit the user's needs, and use the configured virtual machine instances to run the code. Alternatively, the user may send a code execution request to the virtual compute system **110**. The virtual compute system **110** can handle the acquisition and configuration of compute capacity (e.g., containers, instances, etc., which are described in greater detail below) based on the code execution request, and execute the code using the compute capacity. The virtual compute system **110** may automatically scale up and down based on the volume, thereby relieving the user from the burden of having to worry about over-utilization (e.g., acquiring too little computing resources and suffering performance issues) or under-utilization (e.g., acquiring more computing resources than necessary to run the codes, and thus overpaying).

The frontend **120** processes all the requests to execute user code on the virtual compute system **110**. In one embodiment, the frontend **120** serves as a front door to all the other services provided by the virtual compute system **110**. The frontend **120** processes the requests and makes sure that the requests are properly authorized. For example, the frontend **120** may determine whether the user associated with the request is authorized to access the user code specified in the request.

The user code as used herein may refer to any program code (e.g., a program, routine, subroutine, thread, etc.) written in a specific program language. In the present disclosure, the terms "code," "user code," and "program code," may be used interchangeably. Such user code may be executed to achieve a specific task, for example, in connection with a particular web application or mobile application developed by the user. For example, the user codes may be written in JavaScript (node.js), Java, Python, and/or Ruby. The request may include the user code (or the location thereof) and one or more arguments to be used for executing the user code. For example, the user may provide the user code along with the request to execute the user code. In another example, the request may identify a previously uploaded program code (e.g., using the API for uploading the code) by its name or its unique ID. In yet another example, the code may be included in the request as well as uploaded in a separate location (e.g., the storage service **108** or a storage system internal to the virtual compute system **110**) prior to the request is received by the virtual compute system **110**. The virtual compute system **110** may vary its code execution strategy based on where the code is available at the time the request is processed.

The frontend **120** may receive the request to execute such user codes in response to Hypertext Transfer Protocol Secure (HTTPS) requests from a user. Also, any information (e.g., headers and parameters) included in the HTTPS request may also be processed and utilized when executing the user code. As discussed above, any other protocols, including, for example, HTTP, MQTT, and CoAP, may be used to transfer the message containing the code execution request to the frontend **120**. The frontend **120** may also receive the request to execute such user codes when an event is detected, such as an event that the user has registered to

trigger automatic request generation. For example, the user may have registered the user code with an auxiliary service **106** and specified that whenever a particular event occurs (e.g., a new file is uploaded), the request to execute the user code is sent to the frontend **120**. Alternatively, the user may have registered a timed job (e.g., execute the user code every 24 hours). In such an example, when the scheduled time arrives for the timed job, the request to execute the user code may be sent to the frontend **120**. In yet another example, the frontend **120** may have a queue of incoming code execution requests, and when the user's batch job is removed from the virtual compute system's work queue, the frontend **120** may process the user request. In yet another example, the request may originate from another component within the virtual compute system **110** or other servers or services not illustrated in FIG. **1**.

A user request may specify one or more third-party libraries (including native libraries) to be used along with the user code. In one embodiment, the user request is a ZIP file containing the user code and any libraries (and/or identifications of storage locations thereof). In some embodiments, the user request includes metadata that indicates the program code to be executed, the language in which the program code is written, the user associated with the request, and/or the computing resources (e.g., memory, etc.) to be reserved for executing the program code. For example, the program code may be provided with the request, previously uploaded by the user, provided by the virtual compute system **110** (e.g., standard routines), and/or provided by third parties. In some embodiments, such resource-level constraints (e.g., how much memory is to be allocated for executing a particular user code) are specified for the particular user code, and may not vary over each execution of the user code. In such cases, the virtual compute system **110** may have access to such resource-level constraints before each individual request is received, and the individual requests may not specify such resource-level constraints. In some embodiments, the user request may specify other constraints such as permission data that indicates what kind of permissions that the request has to execute the user code. Such permission data may be used by the virtual compute system **110** to access private resources (e.g., on a private network).

In some embodiments, the user request may specify the behavior that should be adopted for handling the user request. In such embodiments, the user request may include an indicator for enabling one or more execution modes in which the user code associated with the user request is to be executed. For example, the request may include a flag or a header for indicating whether the user code should be executed in a debug mode in which the debugging and/or logging output that may be generated in connection with the execution of the user code is provided back to the user (e.g., via a console user interface). In such an example, the virtual compute system **110** may inspect the request and look for the flag or the header, and if it is present, the virtual compute system **110** may modify the behavior (e.g., logging facilities) of the container in which the user code is executed, and cause the output data to be provided back to the user. In some embodiments, the behavior/mode indicators are added to the request by the user interface provided to the user by the virtual compute system **110**. Other features such as source code profiling, remote debugging, etc. may also be enabled or disabled based on the indication provided in the request.

In some embodiments, the virtual compute system **110** may include multiple frontends **120**. In such embodiments, a load balancer may be provided to distribute the incoming requests to the multiple frontends **120**, for example, in a round-robin fashion. In some embodiments, the manner in which the load balancer distributes incoming requests to the multiple frontends **120** may be based on the state of the warming pool **130**A and/or the active pool **140**A. For example, if the capacity in the warming pool **130**A is deemed to be sufficient, the requests may be distributed to the multiple frontends **120** based on the individual capacities of the frontends **120** (e.g., based on one or more load balancing restrictions). On the other hand, if the capacity in the warming pool **130**A is less than a threshold amount, one or more of such load balancing restrictions may be removed such that the requests may be distributed to the multiple frontends **120** in a manner that reduces or minimizes the number of virtual machine instances taken from the warming pool **130**A. For example, even if, according to a load balancing restriction, a request is to be routed to Frontend A, if Frontend A needs to take an instance out of the warming pool **130**A to service the request but Frontend B can use one of the instances in its active pool to service the same request, the request may be routed to Frontend B.

The warming pool manager **130** ensures that virtual machine instances are ready to be used by the worker manager **140** when the virtual compute system **110** receives a request to execute user code on the virtual compute system **110**. In the example illustrated in FIG. **1**, the warming pool manager **130** manages the warming pool **130**A, which is a group (sometimes referred to as a pool) of pre-initialized and pre-configured virtual machine instances that may be used to service incoming user code execution requests. In some embodiments, the warming pool manager **130** causes virtual machine instances to be booted up on one or more physical computing machines within the virtual compute system **110** and added to the warming pool **130**A. In other embodiments, the warming pool manager **130** communicates with an auxiliary virtual management instance service (e.g., an auxiliary service **106** of FIG. **1**) to create and add new instances to the warming pool **130**A. For example, the warming pool manager **130** may cause additional instances to be added to the warming pool **130**A based on the available capacity in the warming pool **130**A to service incoming requests. In some embodiments, the warming pool manager **130** may utilize both physical computing devices within the virtual compute system **110** and one or more virtual machine instance services to acquire and maintain compute capacity that can be used to service code execution requests received by the frontend **120**. In some embodiments, the virtual compute system **110** may comprise one or more logical knobs or switches for controlling (e.g., increasing or decreasing) the available capacity in the warming pool **130**A. For example, a system administrator may use such a knob or switch to increase the capacity available (e.g., the number of pre-booted instances) in the warming pool **130**A during peak hours. In some embodiments, virtual machine instances in the warming pool **130**A can be configured based on a predetermined set of configurations independent from a specific user request to execute a user's code. The predetermined set of configurations can correspond to various types of virtual machine instances to execute user codes. The warming pool manager **130** can optimize types and numbers of virtual machine instances in the warming pool **130**A based on one or more metrics related to current or previous user code executions.

As shown in FIG. **1**, instances may have operating systems (OS) and/or language runtimes loaded thereon. For example, the warming pool **130**A managed by the warming

pool manager **130** comprises instances **152**, **154**. The instance **152** includes an OS **152**A and a runtime **152**B. The instance **154** includes an OS **154**A. In some embodiments, the instances in the warming pool **130**A may also include containers (which may further contain copies of operating systems, runtimes, user codes, etc.), which are described in greater detail below. Although the instance **152** is shown in FIG. **1** to include a single runtime, in other embodiments, the instances depicted in FIG. **1** may include two or more runtimes, each of which may be used for running a different user code. In some embodiments, the warming pool manager **130** may maintain a list of instances in the warming pool **130**A. The list of instances may further specify the configuration (e.g., OS, runtime, container, etc.) of the instances.

In some embodiments, the virtual machine instances in the warming pool **130**A may be used to serve any user's request. In one embodiment, all the virtual machine instances in the warming pool **130**A are configured in the same or substantially similar manner. In another embodiment, the virtual machine instances in the warming pool **130**A may be configured differently to suit the needs of different users. For example, the virtual machine instances may have different operating systems, different language runtimes, and/or different libraries loaded thereon. In yet another embodiment, the virtual machine instances in the warming pool **130**A may be configured in the same or substantially similar manner (e.g., with the same OS, language runtimes, and/or libraries), but some of those instances may have different container configurations. For example, one instance might have a container created therein for running code written in Python, and another instance might have a container created therein for running code written in Ruby. In some embodiments, multiple warming pools **130**A, each having identically-configured virtual machine instances, are provided.

The warming pool manager **130** may pre-configure the virtual machine instances in the warming pool **130**A, such that each virtual machine instance is configured to satisfy at least one of the operating conditions that may be requested or specified by the user request to execute program code on the virtual compute system **110**. In one embodiment, the operating conditions may include program languages in which the potential user codes may be written. For example, such languages may include Java, JavaScript, Python, Ruby, and the like. In some embodiments, the set of languages that the user codes may be written in may be limited to a predetermined set (e.g., set of 4 languages, although in some embodiments sets of more or less than four languages are provided) in order to facilitate pre-initialization of the virtual machine instances that can satisfy requests to execute user codes. For example, when the user is configuring a request via a user interface provided by the virtual compute system **110**, the user interface may prompt the user to specify one of the predetermined operating conditions for executing the user code. In another example, the service-level agreement (SLA) for utilizing the services provided by the virtual compute system **110** may specify a set of conditions (e.g., programming languages, computing resources, etc.) that user requests should satisfy, and the virtual compute system **110** may assume that the requests satisfy the set of conditions in handling the requests. In another example, operating conditions specified in the request may include: the amount of compute power to be used for processing the request; the type of the request (e.g., HTTP vs. a triggered event); the timeout for the request (e.g., threshold time after which the request may be terminated); security policies (e.g., may control which instances in the warming pool **130**A are usable by which user); and etc.

The worker manager **140** manages the instances used for servicing incoming code execution requests. In the example illustrated in FIG. **1**, the worker manager **140** manages the active pool **140**A, which is a group (sometimes referred to as a pool) of virtual machine instances that are currently assigned to one or more users. Although the virtual machine instances are described here as being assigned to a particular user, in some embodiments, the instances may be assigned to a group of users, such that the instance is tied to the group of users and any member of the group can utilize resources on the instance. For example, the users in the same group may belong to the same security group (e.g., based on their security credentials) such that executing one member's code in a container on a particular instance after another member's code has been executed in another container on the same instance does not pose security risks. Similarly, the worker manager **140** may assign the instances and the containers according to one or more policies that dictate which requests can be executed in which containers and which instances can be assigned to which users. An example policy may specify that instances are assigned to collections of users who share the same account (e.g., account for accessing the services provided by the virtual compute system **110**). In some embodiments, the requests associated with the same user group may share the same containers (e.g., if the user codes associated therewith are identical). In some embodiments, a request does not differentiate between the different users of the group and simply indicates the group to which the users associated with the requests belong.

As shown in FIG. **1**, instances may have operating systems (OS), language runtimes, and containers. The containers may have individual copies of the OS and the runtimes and user codes loaded thereon. In the example of FIG. **1**, the active pool **140**A managed by the worker manager **140** includes the instances **156**, **158**. The instance **156** has an OS **156**A, runtimes **156**B, **156**C, and containers **156**D, **156**E. The container **156**D includes a copy of the OS **156**A, a copy of the runtime **156**B, and a copy of a code **156**D-**1**. The container **156**E includes a copy of the OS **156**A, a copy of the runtime **156**C, and a copy of a code **156**E-**1**. The instance **158** has an OS **158**A, runtimes **158**B, **158**C, **158**E, **158**F, a container **158**D, and codes **158**G, **158**H. The container **158**D has a copy of the OS **158**A, a copy of the runtime **158**B, and a copy of a code **158**D-**1**. As illustrated in FIG. **1**, instances may have user codes loaded thereon, and containers within those instances may also have user codes loaded therein. In some embodiments, the worker manager **140** may maintain a list of instances in the active pool **140**A. The list of instances may further specify the configuration (e.g., OS, runtime, container, etc.) of the instances. In some embodiments, the worker manager **140** may have access to a list of instances in the warming pool **130**A (e.g., including the number and type of instances). In other embodiments, the worker manager **140** requests compute capacity from the warming pool manager **130** without having knowledge of the virtual machine instances in the warming pool **130**A.

In the example illustrated in FIG. **1**, user codes are executed in isolated virtual compute systems referred to as containers (e.g., containers **156**D, **156**E, **158**D). Containers are logical units created within a virtual machine instance using the resources available on that instance. For example, the worker manager **140** may, based on information specified in the request to execute user code, create a new container or locate an existing container in one of the instances in the active pool **140**A and assigns the container

to the request to handle the execution of the user code associated with the request. In one embodiment, such containers are implemented as Linux containers.

Once a request has been successfully processed by the frontend **120**, the worker manager **140** finds capacity to service the request to execute user code on the virtual compute system **110**. For example, if there exists a particular virtual machine instance in the active pool **140**A that has a container with the same user code loaded therein (e.g., code **156**D-**1** shown in the container **156**D), the worker manager **140** may assign the container to the request and cause the user code to be executed in the container. Alternatively, if the user code is available in the local cache of one of the virtual machine instances (e.g., codes **158**G, **158**H, which are stored on the instance **158** but do not belong to any individual containers), the worker manager **140** may create a new container on such an instance, assign the container to the request, and cause the used code to be loaded and executed in the container.

If the worker manager **140** determines that the user code associated with the request is not found on any of the instances (e.g., either in a container or the local cache of an instance) in the active pool **140**A, the worker manager **140** may determine whether any of the instances in the active pool **140**A is currently assigned to the user associated with the request and has compute capacity to handle the current request. If there is such an instance, the worker manager **140** may create a new container on the instance and assign the container to the request. Alternatively, the worker manager **140** may further configure an existing container on the instance assigned to the user, and assign the container to the request. For example, the worker manager **140** may determine that the existing container may be used to execute the user code if a particular library demanded by the current user request is loaded thereon. In such a case, the worker manager **140** may load the particular library and the user code onto the container and use the container to execute the user code.

If the active pool **140** does not contain any instances currently assigned to the user, the worker manager **140** pulls a new virtual machine instance from the warming pool **130**A, assigns the instance to the user associated with the request, creates a new container on the instance, assigns the container to the request, and causes the user code to be downloaded and executed on the container.

In some embodiments, the virtual compute system **110** is adapted to begin execution of the user code shortly after it is received (e.g., by the frontend **120**). A time period can be determined as the difference in time between initiating execution of the user code (e.g., in a container on a virtual machine instance associated with the user) and receiving a request to execute the user code (e.g., received by a frontend). The virtual compute system **110** is adapted to begin execution of the user code within a time period that is less than a predetermined duration. In one embodiment, the predetermined duration is 500 ms. In another embodiment, the predetermined duration is 300 ms. In another embodiment, the predetermined duration is 100 ms. In another embodiment, the predetermined duration is 50 ms. In another embodiment, the predetermined duration is 10 ms. In another embodiment, the predetermined duration may be any value chosen from the range of 10 ms to 500 ms. In some embodiments, the virtual compute system **110** is adapted to begin execution of the user code within a time period that is less than a predetermined duration if one or more conditions are satisfied. For example, the one or more conditions may include any one of: (1) the user code is loaded on a container in the active pool **140** at the time the request is received; (2) the user code is stored in the code cache of an instance in the active pool **140** at the time the request is received; (3) the active pool **140**A contains an instance assigned to the user associated with the request at the time the request is received; or (4) the warming pool **130**A has capacity to handle the request at the time the request is received.

The user code may be downloaded from an auxiliary service **106** such as the storage service **108** of FIG. **1**. Data **108**A illustrated in FIG. **1** may comprise user codes uploaded by one or more users, metadata associated with such user codes, or any other data utilized by the virtual compute system **110** to perform one or more techniques described herein. Although only the storage service **108** is illustrated in the example of FIG. **1**, the virtual environment **100** may include other levels of storage systems from which the user code may be downloaded. For example, each instance may have one or more storage systems either physically (e.g., a local storage resident on the physical computing system on which the instance is running) or logically (e.g., a network-attached storage system in network communication with the instance and provided within or outside of the virtual compute system **110**) associated with the instance on which the container is created. Alternatively, the code may be downloaded from a web-based data store provided by the storage service **108**.

Once the worker manager **140** locates one of the virtual machine instances in the warming pool **130**A that can be used to serve the user code execution request, the warming pool manager **130** or the worker manger **140** takes the instance out of the warming pool **130**A and assigns it to the user associated with the request. The assigned virtual machine instance is taken out of the warming pool **130**A and placed in the active pool **140**A. In some embodiments, once the virtual machine instance has been assigned to a particular user, the same virtual machine instance cannot be used to service requests of any other user. This provides security benefits to users by preventing possible co-mingling of user resources. Alternatively, in some embodiments, multiple containers belonging to different users (or assigned to requests associated with different users) may co-exist on a single virtual machine instance. Such an approach may improve utilization of the available compute capacity.

In some embodiments, the virtual compute system **110** may maintain a separate cache in which user codes are stored to serve as an intermediate level of caching system between the local cache of the virtual machine instances and a web-based network storage (e.g., accessible via the network **104**). The various scenarios that the worker manager **140** may encounter in servicing the request are described in greater detail below with reference to FIG. **4**.

After the user code has been executed, the worker manager **140** may tear down the container used to execute the user code to free up the resources it occupied to be used for other containers in the instance. Alternatively, the worker manager **140** may keep the container running to use it to service additional requests from the same user. For example, if another request associated with the same user code that has already been loaded in the container, the request can be assigned to the same container, thereby eliminating the delay associated with creating a new container and loading the user code in the container. In some embodiments, the worker manager **140** may tear down the instance in which the container used to execute the user code was created. Alternatively, the worker manager **140** may keep the instance running to use it to service additional requests from the same

user. The determination of whether to keep the container and/or the instance running after the user code is done executing may be based on a threshold time, the type of the user, average request volume of the user, and/or other operating conditions. For example, after a threshold time has passed (e.g., 5 minutes, 30 minutes, 1 hour, 24 hours, 30 days, etc.) without any activity (e.g., running of the code), the container and/or the virtual machine instance is shutdown (e.g., deleted, terminated, etc.), and resources allocated thereto are released. In some embodiments, the threshold time passed before a container is torn down is shorter than the threshold time passed before an instance is torn down.

In some embodiments, the virtual compute system **110** may provide data to one or more of the auxiliary services **106** as it services incoming code execution requests. For example, the virtual compute system **110** may communicate with the monitoring/logging/billing services **107**. The monitoring/logging/billing services **107** may include: a monitoring service for managing monitoring information received from the virtual compute system **110**, such as statuses of containers and instances on the virtual compute system **110**; a logging service for managing logging information received from the virtual compute system **110**, such as activities performed by containers and instances on the virtual compute system **110**; and a billing service for generating billing information associated with executing user code on the virtual compute system **110** (e.g., based on the monitoring information and/or the logging information managed by the monitoring service and the logging service). In addition to the system-level activities that may be performed by the monitoring/logging/billing services **107** (e.g., on behalf of the virtual compute system **110**) as described above, the monitoring/logging/billing services **107** may provide application-level services on behalf of the user code executed on the virtual compute system **110**. For example, the monitoring/logging/billing services **107** may monitor and/or log various inputs, outputs, or other data and parameters on behalf of the user code being executed on the virtual compute system **110**. Although shown as a single block, the monitoring, logging, and billing services **107** may be provided as separate services.

In some embodiments, the worker manager **140** may perform health checks on the instances and containers managed by the worker manager **140** (e.g., those in the active pool **140**A). For example, the health checks performed by the worker manager **140** may include determining whether the instances and the containers managed by the worker manager **140** have any issues of (1) misconfigured networking and/or startup configuration, (2) exhausted memory, (3) corrupted file system, (4) incompatible kernel, and/or any other problems that may impair the performance of the instances and the containers. In one embodiment, the worker manager **140** performs the health checks periodically (e.g., every 5 minutes, every 30 minutes, every hour, every 24 hours, etc.). In some embodiments, the frequency of the health checks may be adjusted automatically based on the result of the health checks. In other embodiments, the frequency of the health checks may be adjusted based on user requests. In some embodiments, the worker manager **140** may perform similar health checks on the instances and/or containers in the warming pool **130**A. The instances and/or the containers in the warming pool **130**A may be managed either together with those instances and containers in the active pool **140**A or separately. In some embodiments, in the case where the health of the instances and/or the containers in the warming pool **130**A is managed separately from the active pool **140**A, the warming pool manager **130**, instead of the worker manager **140**, may perform the health checks described above on the instances and/or the containers in the warming pool **130**A.

The worker manager **140** may include an instance allocation unit for finding compute capacity (e.g., containers) to service incoming code execution requests and a user code execution unit for facilitating the execution of user codes on those containers. An example configuration of the worker manager **140** is described in greater detail below with reference to FIG. **2**.

FIG. **2** depicts a general architecture of a computing system (referenced as worker manager **140**) that manages the virtual machine instances in the virtual compute system **110**. The general architecture of the worker manager **140** depicted in FIG. **2** includes an arrangement of computer hardware and software modules that may be used to implement aspects of the present disclosure. The hardware modules may be implemented with physical electronic devices, as discussed in greater detail below. The worker manager **140** may include many more (or fewer) elements than those shown in FIG. **2**. It is not necessary, however, that all of these generally conventional elements be shown in order to provide an enabling disclosure. Additionally, the general architecture illustrated in FIG. **2** may be used to implement one or more of the other components illustrated in FIG. **1**. As illustrated, the worker manager **140** includes a processing unit **190**, a network interface **192**, a computer readable medium drive **194**, an input/output device interface **196**, all of which may communicate with one another by way of a communication bus. The network interface **192** may provide connectivity to one or more networks or computing systems. The processing unit **190** may thus receive information and instructions from other computing systems or services via the network **104**. The processing unit **190** may also communicate to and from memory **180** and further provide output information for an optional display (not shown) via the input/output device interface **196**. The input/output device interface **196** may also accept input from an optional input device (not shown).

The memory **180** may contain computer program instructions (grouped as modules in some embodiments) that the processing unit **190** executes in order to implement one or more aspects of the present disclosure. The memory **180** generally includes RAM, ROM and/or other persistent, auxiliary or non-transitory computer readable media. The memory **180** may store an operating system **184** that provides computer program instructions for use by the processing unit **190** in the general administration and operation of the worker manager **140**. The memory **180** may further include computer program instructions and other information for implementing aspects of the present disclosure. For example, in one embodiment, the memory **180** includes a user interface unit **182** that generates user interfaces (and/or instructions therefor) for display upon a computing device, e.g., via a navigation and/or browsing interface such as a browser or application installed on the computing device. In addition, the memory **180** may include and/or communicate with one or more data repositories (not shown), for example, to access user program codes and/or libraries.

In addition to and/or in combination with the user interface unit **182**, the memory **180** may include an instance allocation unit **186** and a user code execution unit **188** that may be executed by the processing unit **190**. In one embodiment, the user interface unit **182**, instance allocation unit **186**, and user code execution unit **188** individually or collectively implement various aspects of the present dis-

closure, e.g., finding compute capacity (e.g., a container) to be used for executing user code, causing the user code to be loaded and executed on the container, etc. as described further below.

The instance allocation unit **186** finds the compute capacity to be used for servicing a request to execute user code. For example, the instance allocation unit **186** identifies a virtual machine instance and/or a container that satisfies any constraints specified by the request and assigns the identified virtual machine instance and/or container to the user or the request itself. The instance allocation unit **186** may perform such identification based on the programming language in which the user code is written. For example, if the user code is written in Python, and the instance allocation unit **186** may find an virtual machine instance (e.g., in the warming pool **130**A of FIG. **1**) having the Python runtime pre-loaded thereon and assign the virtual machine instance to the user. In another example, if the program code specified in the request of the user is already loaded on an existing container or on another virtual machine instance assigned to the user (e.g., in the active pool **140**A of FIG. **1**), the instance allocation unit **186** may cause the request to be processed in the container or in a new container on the virtual machine instance. In some embodiments, if the virtual machine instance has multiple language runtimes loaded thereon, the instance allocation unit **186** may create a new container on the virtual machine instance and load the appropriate language runtime on the container based on the computing constraints specified in the request.

The user code execution unit **188** manages the execution of the program code specified by the request of the user once a particular virtual machine instance has been assigned to the user associated with the request and a container on the particular virtual machine instance has been assigned to the request. If the code is pre-loaded in a container on the virtual machine instance assigned to the user, the code is simply executed in the container. If the code is available via a network storage (e.g., storage service **108** of FIG. **1**), the user code execution unit **188** downloads the code into a container on the virtual machine instance and causes the code to be executed (e.g., by communicating with the frontend **120** of FIG. **1**) once it has been downloaded.

While the instance allocation unit **186** and the user code execution unit **188** are shown in FIG. **2** as part of the worker manager **140**, in other embodiments, all or a portion of the instance allocation unit **186** and the user code execution unit **188** may be implemented by other components of the virtual compute system **110** and/or another computing device. For example, in certain embodiments of the present disclosure, another computing device in communication with the virtual compute system **110** may include several modules or components that operate similarly to the modules and components illustrated as part of the worker manager **140**.

In some embodiments, the worker manager **140** may further include components other than those illustrated in FIG. **2**. For example, the memory **180** may further include a container manager for managing creation, preparation, and configuration of containers within virtual machine instances.

Turning now to FIG. **3**, a routine **300** implemented by one or more components of the virtual compute system **110** (e.g., the worker manager **140**) will be described. Although routine **300** is described with regard to implementation by the worker manager **140**, one skilled in the relevant art will appreciate that alternative components may implement routine **300** or that one or more of the blocks may be implemented by a different component or in a distributed manner.

At block **302** of the illustrative routine **300**, the worker manager **140** receives a request to execute user code. Alternatively, the worker manager **140** receives a request from the frontend **120** of FIG. **1** to find compute capacity for executing the user code associated with an incoming request received and processed by the frontend **120**. For example, the frontend **120** may process the request received from the user computing devices **102** or the auxiliary services **106**, and forward the request to the worker manager **140** after authenticating the user and determining that the user is authorized to access the specified user code. As discussed above, the request may include data or metadata that indicates the program code to be executed, the language in which the program code is written, the user associated with the request, and/or the computing resources (e.g., memory, etc.) to be reserved for executing the program code. For example, the request may specify that the user code is to be executed on "Operating System A" using "Language Runtime X." In such an example, the worker manager **140** may locate a virtual machine instance that has been pre-configured with "Operating System A" and "Language Runtime X" and assigned it to the user. The worker manager **140** may then create a container on the virtual machine instance for executing the user code therein.

Next, at block **304**, the worker manager **140** acquires compute capacity based on the information indicated in the request. In some embodiments, the compute capacity comprises a container that is configured to service the code execution request. As discussed herein, the container may be acquired from the active pool **140**A or the warming pool **130**A. How the compute capacity is acquired is described in greater detail below with reference to FIG. **4**.

At block **306**, the worker manager **140** causes the user code to be executed using the compute capacity. For example, the worker manager **140** may send the address of the container assigned to the request to the frontend **120** so that the frontend **120** can proxy the code execution request to the address. In some embodiments, the address may be temporarily reserved by the worker manager **140** and the address and/or the container may automatically be released after a specified time period elapses. In some embodiments, the address and/or the container may automatically be released after the user code has finished executing in the container.

While the routine **300** of FIG. **3** has been described above with reference to blocks **302-306**, the embodiments described herein are not limited as such, and one or more blocks may be omitted, modified, or switched without departing from the spirit of the present disclosure. For example, the block **302** may be modified such that the worker manager **140** receives a compute capacity acquisition request from the frontend **120**.

FIG. **4** is a block diagram illustrating one embodiment of processes of virtual machine instance management to process a request to execute user code.

At (1), the frontend **120** of a virtual compute system **110** receives a request to execute or to deploy a user code. The request can be transmitted from a user computing device **102**. In some embodiments, the request can be received from one of the auxiliary services **106**. For example, in some embodiments, an auxiliary service can be adapted to generate a request based on an event associated with the auxiliary services **106**. Additional examples of auxiliary service event generation, including event triggering, are described in U.S. application Ser. No. 14/502,648, filed Sep. 30, 2014, titled PROGRAMMATIC EVENT DETECTION AND MESSAGE GENERATION FOR REQUESTS TO

EXECUTE PROGRAM CODE, which is expressly incorporated by reference in its entirety. The request can be a request to execute or deploy a program code included in the request or a program code stored in a separate computing system. Various program languages including Java, PHP, C++, Python, etc. can be used to compose the user code. The request can include configuration information relating to code-execution requirements. For example, the request can include information about program language in which the program code is written, information about language runtime and/or language library to execute the user code. The configuration information need not include any specific information regarding the virtual machine instance that can host the user code. The request can also include information that specifies policies of reporting/storing of user code execution results/activities. For example, the request can specify that result of user code execution will be reported synchronously or asynchronously (batch) to the computing device that transmitted user code execution request. Also, the request may specify that user code execution result will be stored by an auxiliary service **106** with or without synchronous reporting of the result. The request can include configuration information specified by users or determined by the frontend regarding to execution of user code. The configuration information can correspond to hardware or software requirements to execute the user code. For example, the configuration information can correspond to selection of a specific type among predetermined types of virtual machine instances which may be available in the warming pool **130** or in the active pool **140**A. The virtual machine types can vary based upon predetermined sets of hardware (e.g., memory, processor, storage, etc.) and software (e.g., operating system, runtime environment, libraries, etc.) resources available to containers created within the virtual machine. In some embodiments, the configuration information can specify allowable latency to acquire compute capacity in response to user code execution request. Procedures and policies to acquire compute capacity can vary based on the allowable latency.

At (2), the frontend **120** processes the request. The frontend **120** can analyze the request and format the request into a message that can be further processed by the virtual compute system **110**. Additional examples of frontend processing are described in U.S. application Ser. No. 14/502,741, filed Sep. 30, 2014, titled PROCESSING EVENT MESSAGES FOR USER REQUESTS TO EXECUTE PROGRAM CODE, which is expressly incorporated by reference in its entirety.

In some embodiments, the frontend **120** can analyze a user code associated with a request from the user computing device **102** and determine what type of configuration is suitable to execute the user code. For example, the frontend **120** can identify information about the programming language of the user code based on header information or metadata associated with the user code. In some other embodiments, the frontend **120** can forward the request from the user computing device **102** to the worker manager **140** without analyzing the request or user code.

With continued reference to FIG. **4**, at (3), the frontend **120** sends a message for user code execution to a worker manager **140**. The worker manager **140** initiates a process to locate or acquire compute capacity for user code execution based on the received message. For example, the worker manager **140** can locate a container already created on a virtual machine instance that is already associated with the user at the time the request is received or processed. In another embodiment, the worker manager **140** can locate an instance that is already associated with the user at the time the request is received or processed, even if a container suitable for executing the user's code has not yet been created. In another embodiment, the worker manager can obtain an already-created (e.g., warmed) instance from a warming pool, associate it with the user, and create a container within the instance for executing the user's code. In some cases, warmed containers may be created within warmed instances prior to receiving or processing user requests for code deployment.

At (4), the worker manager **140** can acquire compute capacity to execute or deploy user code. Acquiring compute capacity can be conducted based on one or more of operation policies of the virtual compute system **110** or configuration information specified in the user code execution requests (or implied by the user code execution requests). The worker manager **140** can determine resource requirements based on the configuration information and create at least one container that meets the resource requirements. Priorities and limitations in acquiring compute capacity may be associated with various factors including latency in responding requests (time to acquire compute capacity after receiving requests), billing constraints and security policies. In some embodiments, to reduce latency in responding the request, the worker manager **140** tries to allocate an existing container to host user code execution because creating a new container may take longer than utilizing an existing container. If there is no available, existing container suitable to hose the user code, the worker manager **140** can create a new container in an active virtual machine instance associated with the user. Such active virtual machine instance may be located in the active pool **140**A. Allocating a new instance from the warming pool **130**A may take longer than utilizing an active instance of the active pool **140**A. If there is no available, active virtual machine instance associated with the user, the worker manager **140** can allocate a new virtual machine instance from the warming pool **130**A and create a container within it to host user code execution. This may result in higher latency than utilizing an active instance or an existing container within an active instance. In some embodiments, acquiring compute capacity can be performed based on operation cost and billing constraints. For example, allocation of containers/instances can be determined to save operation cost of the virtual compute or to meet billing constraints in spite of higher latency.

At (4), the worker manager **140** identifies a virtual machine instance that matches the configuration information included within the message transmitted from the frontend **120**. The worker manager **140** can compare configuration settings of virtual machine instances in the warming pool **130**A with configuration information of the request to identify a matching virtual machine instance suitable to execute the user's code. In some embodiments, in response to a request, the worker manager **140** can identify a virtual machine instance already assigned to the same user account with which the request is associated. When resources of a virtual machine instance are reserved exclusively for a specific user, a security policy may permit the virtual machine instance to deploy other user code from the same user. Therefore, prior to checking availability of a virtual machine instance in the warming pool **130**A, the worker manager **140** can check available resources of an active virtual machine instance hosting other code associated with the same user. However, in some embodiments, whether or not currently active virtual machine instances having matching configuration information exist, user code can be assigned to a new virtual machine instance when specified

by the request or determined based on the requirement of user code. If the worker manager **140** determines that there is no capacity in a virtual machine instance already allocated to the same user, or that there are no virtual machine instances already allocated to the user, the worker manager **140** requests a new virtual machine instance from the warming pool **130**A.

Also, when the request includes a request to update user code which has been already deployed in the virtual compute system **110**, the worker manager **140** can identify virtual machine instances hosting an old version of user code and start the process to update the old version of user code with a new version of user code associated with the request. In some embodiments, containers hosting an old version of user code may continue to execute the old version of user code until an updated version of the user code is loaded on the containers. In some embodiments, the worker manager **140** can cause containers to stop execution of an old version of user code promptly or immediately in response to a request to update user code.

The worker manager **140** can allocate the identified virtual machine instance to a user associated with the request. The allocated virtual machine instance is now part of the active pool **140**A rather than the warming pool **130**A and will be managed by the worker manager **140**. Association of a virtual machine instance can be exclusive to a specific user account for security purposes. In some embodiments, to prevent execution of user code associated with a specific user account from affecting execution of user code associated with the other users, a virtual machine instance can host user code associated with a specific user but cannot host user code associated with the other users. Association of the virtual machine instance to a specific user account can be conducted by modifying data entry of a database storing information of virtual machine instances controlled by the worker manager **140**.

The worker manager **140** can create and/or allocate a container inside a virtual machine instance allocated to execute/deploy a particular user's code. A portion of the virtual machine instance's resources is reserved for container allocation. The worker manager **140** can also configure the virtual machine container for executing/deploying the user codes. For example, language runtimes and libraries used to run the user's code can be loaded into the virtual machine container based on the configuration information associated with the request from the user computing device **102**. The worker manager **140** can deploy user codes on the container configured with software components corresponding to configuration information or resource requirements associated with the user codes. Actual execution of deployed user code can be initiated by a subsequent request from a user device or a separate computing system.

At (5), the worker manager **140** manages user code execution by a virtual machine instance that has a container that has been designated to execute the user's code. The worker manager **140** can communicate with other components, systems, and services associated with the virtual compute system **110**, as well. For example, the worker manager **140** can facilitates communication between a virtual machine instance and a storage service (e.g., the storage service **108** of FIG. **1**). In addition, the worker manager **140** can manage capacities and/or configurations of virtual machine instances in the active pool **140**A, as discussed above. Once the user's code is loaded into a container of a designated virtual machine instance, the container executes the user's code. In some embodiments, the virtual compute system **110** is adapted to begin execution of the user code shortly after it is received (e.g., by the frontend **120**). A time period can be determined as the difference in time between initiating execution of the user code (e.g., in a container on a virtual machine instance associated with the user) and receiving a request to execute the user code (e.g., received by a frontend). The virtual compute system **110** is adapted to begin execution of the user code within a time period that is less than a predetermined duration. In one embodiment, the predetermined duration is 500 ms. In another embodiment, the predetermined duration is 300 ms. In another embodiment, the predetermined duration is 100 ms. In another embodiment, the predetermined duration is 50 ms. In another embodiment, the predetermined duration is 10 ms. In another embodiment, the predetermined duration may be any value chosen from the range of 10 ms to 500 ms. In some embodiments, the virtual compute system **110** is adapted to begin execution of the user code within a time period that is less than a predetermined duration if one or more conditions are satisfied. For example, the one or more conditions may include any one of: (1) the user code is loaded on a container in the active pool **140** at the time the request is received; (2) the user code is stored in the code cache of an instance in the active pool **140** at the time the request is received; (3) the active pool **140**A contains an instance assigned to the user associated with the request at the time the request is received; or (4) the warming pool **130**A has capacity to handle the request at the time the request is received. The results of the execution may be output to user devices, storage system associated with the user, or a separate storage service as discussed below. For example, the results of a calculation or process performed by the container (e.g., generate a thumbnail image of an image stored at within a storage service) can be stored in a storage service **108** accessible by the user.

With continued reference to FIG. **4**, at (6), the worker manager **140** communicates with the frontend **120** to provide result of user code execution to the user computing device **102**. At (7), the virtual compute system **110** (e.g., the frontend **120** or a worker manager) communicates processing result of user code execution request with the user computing device **102** and/or or auxiliary services **106**. In some embodiments, results are not communicated to the user or a service. Such results may be stored and used by the virtual compute system **110** for additional processing. Result information may be used to generate a report of operation status, resource usage and billing information based on the communicated processing result.

At (8), the virtual compute system **110** communicates with auxiliary services **106** to provide monitoring and/or logging information associated with the virtual compute system **110**. In some embodiments, an activity log can be stored by auxiliary services **106**. The activity log can be used to generate billing communications with the user. The virtual compute system **110** can transmit monitoring information to the monitoring/logging/billing services **107** (which can be separate services). The monitoring/logging information can include application level information regarding activities associated with user code execution and system level information regarding status and health of virtual machine instances in the virtual compute system **110**. The monitoring information and logging information can be utilized to initiate processes to optimize inventory of instances/containers in the virtual compute system **110** including creation, acquisition, relocation, compaction and recycling of instances/containers. The instance/container inventory optimization can be conducted based on various factors includ-

ing cost of operation, latency in responding user code execution requests, security, system scalability and system stability.

With continued reference to FIG. **4**, the virtual compute system **110** can create and manage virtual machine instances to process user code execution requests independently from and asynchronously with respect to receiving requests from user computing devices **102**. For example, the warming pool manager **130** of the virtual compute system **110** can prepare warmed virtual machine instances in the warming pool **130**A prior to receiving a request to execute user code. Warmed virtual machine instances in the warming pool **130**A are not assigned to a specific user and contain software components to support execution of user codes. For example, software components contained in the warmed virtual machine instances include at least one runtime and one or more libraries. In some embodiments, at least some of the warmed instances can be further prepared with warmed containers. Such warmed containers can be configured to contain all or a subset of the copies of the software components of their associated warmed instances. In addition, the virtual compute system **110** can recycle virtual machine instances (e.g., remove virtual machine instances from the active pool **140**A and create new virtual machine instances in the warming pool **130**) also independent of specific requests from user computing devices **102**.

Preparation and configuration of virtual machine instances in the warming pool **130**A can be conducted independently from specific user code execution requests but based on statistics and historic information associated with user code execution requests. For example, the warming pool manager **130** can optimize the various configuration types and numbers of virtual machine instances maintained in the warming pool **130**A using such information. For example, the warming pool manager **130** can determine that it is more likely that an instance having a particular configuration may be in high demand during a particular time of day. Therefore, the warming pool manager **130** may create a larger number of instances having such configuration and place those instances in a warming pool in anticipation of receiving user requests to execute code compatible with such instances.

The virtual compute system **110** can recycle virtual machine instances independent of specific requests from the user computing devices **102** and based on activation history of virtual machine instances and/or user codes. For example, the worker manager **140** can monitors the activation history and identify virtual machine instances within the active pool which have not been used to execute user code for longer than a predetermined time period. The worker manager **140** then invalidates allocation of the identified virtual machine instances to user accounts. Recycling of virtual machine instances can be based on time interval between activation messages (sometimes referred to as a trigger) associated with user code. For example, user code designed to generate thumbnail images of new photographs might require an activation message from a storage service **108** that a new photograph is uploaded. When such activation message is not received for a more than a predetermined time period, virtual machine instances reserved for (associated with) a user account can be de-allocated (un-associated). In this situation, keeping the user code loaded in the virtual machine instance might be a waste of reserved resources. When such a time period passes, the worker manager **140** can determine that the virtual machine instance is not being utilized and it can initiate a process to recycle the idle virtual machine instance.

In some embodiments, communication events with other system or components associated with a virtual machine instance can be analyzed to determine the status of a virtual machine instance. In some embodiment, a history of communication events to store processing result of user code execution can be analyzed to determine whether a virtual machine instance hosting the user code is being utilized actively or not. For example, when a virtual machine instance hosting a user code to generate thumbnail images of new photographs does not communicate with a storage system which stores generated thumbnail images for longer than a predetermined time period, the worker manager **140** can determine that the virtual machine instance is not going to be utilized or that too many instances having a particular configuration are being maintained in the active pool. In some embodiments, the worker manager **140** can initiate relocation or recycling of containers to optimize the numbers of virtual machine instances allocated to a specific user.

It will be appreciated by those skilled in the art and others that all of the functions described in this disclosure may be embodied in software executed by one or more physical processors of the disclosed components and mobile communication devices. The software may be persistently stored in any type of non-volatile storage.

Conditional language, such as, among others, "can," "could," "might," or "may," unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments include, while other embodiments do not include, certain features, elements and/or steps. Thus, such conditional language is not generally intended to imply that features, elements and/or steps are in any way required for one or more embodiments or that one or more embodiments necessarily include logic for deciding, with or without user input or prompting, whether these features, elements and/or steps are included or are to be performed in any particular embodiment.

Any process descriptions, elements, or blocks in the flow diagrams described herein and/or depicted in the attached figures should be understood as potentially representing modules, segments, or portions of code which include one or more executable instructions for implementing specific logical functions or steps in the process. Alternate implementations are included within the scope of the embodiments described herein in which elements or functions may be deleted, executed out of order from that shown or discussed, including substantially concurrently or in reverse order, depending on the functionality involved, as would be understood by those skilled in the art. It will further be appreciated that the data and/or components described above may be stored assume in a computer-readable medium and loaded into memory of the computing device using a drive mechanism associated with a computer readable storage medium storing the computer executable components such as a CD ROM, DVD ROM, or network interface. Further, the component and/or data can be included in a single device or distributed in any manner. Accordingly, general purpose computing devices may be configured to implement the processes, algorithms, and methodology of the present disclosure with the processing and/or execution of the various data and/or components described above.

It should be emphasized that many variations and modifications may be made to the above-described embodiments, the elements of which are to be understood as being among other acceptable examples. All such modifications and variations are intended to be included herein within the scope of this disclosure and protected by the following claims.

What is claimed is:

1. A computer implemented method to process requests to execute user code on one or more virtual machine instances, the method comprising:

as implemented by one or more computing devices configured with specific computer-executable instructions,

providing a plurality of warmed virtual machine instances, each of the warmed virtual machine instances being unassigned to a specific user and containing a software component associated with a programming language;

subsequent to providing the plurality of warmed, unassigned virtual machine instances, receiving a request to execute a user code, the request comprising configuration information associated with executing the user code, wherein the request is received at a first time;

identifying a virtual machine instance from the plurality of warmed virtual machine instances based on the configuration information of the request, wherein the identified virtual machine instance contains a particular software component that is suitable to execute the user code;

associating the identified virtual machine instance with a user account associated with the request;

creating, within the associated virtual machine instance, a container to execute the user code;

loading the particular software component and the user code into the container; and

initiating execution of the user code by the container, wherein said initiating occurs at a second time, and

wherein a time period from the first time to the second time is less than a predetermined duration.

2. The method as recited in claim **1**, wherein the predetermined duration is 100 ms.

3. The method as recited in claim **1**, wherein creating the container further comprises:

receiving a plurality of requests to execute the user code;

creating a plurality of containers within the identified virtual machine instance, wherein each of the plurality of containers is configured based on the configuration information of the request; and

selecting one of the plurality of containers to execute the user code.

4. The method as recited in claim **1**, wherein creating the container further comprises:

receiving a plurality of requests to execute a plurality of user codes;

creating a plurality of containers within the identified virtual machine instance, wherein each of the plurality of containers is configured based on configuration information of the requests; and

selecting one of the plurality of containers to execute the user code.

5. The method as recited in claim **1**, wherein creating the at least one container further comprises:

determining resource requirements using the configuration information; and

creating at least one container having at least the resource requirements.

6. The method as recited in claim **1**, wherein the software component comprises at least one of a runtime or one or more libraries.

7. The method as recited in claim **1**, further comprising:

monitoring an activation history of the user code in the identified virtual machine instance; and

dissociating the identified virtual machine instance from the user account or destroying the container based on the activation history.

8. A system comprising:

a computing device comprising a processor coupled to a memory, the memory including specific instructions that upon execution configure the system to:

provide a plurality of warmed virtual machine instances, each of the warmed virtual machine instances being unassigned to a specific user and containing a software component associated with a programming language;

subsequent to providing the plurality of warmed, unassigned virtual machine instances, receive a request to execute a user code, the request comprising configuration information associated with executing the user code, wherein the request is received at a first time;

identify a virtual machine instance from the plurality of warmed virtual machine instances based on the configuration information of the request, wherein the identified virtual machine instance contains a particular software component that is suitable to execute the user code;

associate the identified virtual machine instance with a user account associated with the request;

create, within the associated virtual machine instance, a container to execute the user code;

load the particular software component and the user code into the container; and

initiate execution of the user code by the container, wherein said initiating occurs at a second time,

wherein a time period from the first time to the second time is less than a predetermined duration.

9. The system as recited in claim **8**, wherein the predetermined duration is 100 ms.

10. The system as recited in claim **8**, wherein the specific instructions further configure the system to provide the plurality of virtual machine instances before receiving the request to execute the user code.

11. The system as recited in claim **8**, wherein the software component comprises at least one of a runtime or one or more libraries.

12. The system as recited in claim **8**, wherein the specific instructions further configure the system to:

monitor an activation history of the user code in the identified virtual machine instance; and

dissociate the identified virtual machine instance from the user account or destroy the container based on the activation history.

13. The system as recited in claim **8**, wherein the identified virtual machine instance comprises the container prior to receiving the request.

14. The system as recited in claim **13**, wherein the container comprises the user code prior to receiving the request.

15. The system as recited in claim **13**, wherein the specific instructions further configure the system to select the container based on resource requirements associated with the request.

16. The system as recited in claim **8**, wherein the specific instructions further configure the system to create the container on the virtual machine instance after receiving the request.

17. A non-transitory, computer-readable storage medium storing computer-executable instructions that, when executed by a computer system, configure the computer system to;

provide a plurality of warmed virtual machine instances, each of the warmed virtual machine instances being unassigned to a specific user and containing a software component associated with a programming language;

subsequent to providing the plurality of warmed, unassigned virtual machine instances, receive a request to execute a user code, the request comprising configuration information associated with executing the user code, wherein the request is received at a first time;

identify a virtual machine instance from the plurality of warmed virtual machine instances based on the configuration information of the request, wherein the identified virtual machine instance contains a particular software component that is suitable to execute the user code;

associate the identified virtual machine instance with a user account associated with the request;

create, within the associated virtual machine instance, a container to execute the user code;

load the particular software component and the user code into the container; and

initiate execution of the user code by the container, wherein said initiating occurs at a second time,

wherein a time period from the first time to the second time is less than a predetermined duration.

18. The non-transitory, computer-readable storage medium as recited in claim **17**, wherein the predetermined duration is 100 ms.

19. The non-transitory, computer-readable storage medium as recited in claim **17**, wherein the instructions further configure the computer system to provide the plurality of virtual machine instances prior to receiving the request.

20. The non-transitory, computer-readable storage medium as recited in claim **17**, wherein the software component comprises at least one of a runtime or one or more libraries.

21. The non-transitory, computer-readable storage medium as recited in claim **17**, wherein the instructions further configure the computer system to

monitor an activation history of the user code in the identified virtual machine instance; and

dissociate the identified virtual machine instance from the user account or destroy the container based on the activation history.

22. The non-transitory, computer-readable storage medium as recited in claim **17**, wherein the identified virtual machine instance comprises the container prior to receiving the request.

23. The non-transitory, computer-readable storage medium as recited in claim **22**, wherein the container comprises the user code prior to receiving the request.

24. The non-transitory, computer-readable storage medium as recited in claim **22**, wherein the instructions further configure the computer system to select the container based on resource requirements associated with the request.

25. The non-transitory, computer-readable storage medium as recited in claim **17**, wherein the instructions further configure the computer system to create the container on the virtual machine instance after receiving the request.

26. A computer implemented method for managing virtual machine instances, the method comprising:

providing a plurality of virtual machine instances, wherein each of the plurality of virtual machine instances contains at least one software component associated with at least one programming language;

receiving a request to execute a user code, the request comprising configuration information associated with the user code, wherein the request is received at a first time;

identifying a virtual machine instance from the plurality of virtual machine instances based on the configuration information of the request, wherein the identified virtual machine instance contains a particular software component that corresponds to the configuration information;

identifying a container having a first copy of the user code loaded thereon within the identified virtual machine instance;

causing the first copy of the user code loaded on the container to be executed based on the configuration information, wherein the first copy of the user code is caused to begin executing within a predetermined duration after the first time;

monitoring an activation history of the user code, wherein the activation history comprises information regarding execution of the user code in the identified virtual machine instance; and

dissociating the identified virtual machine instance from the user account or destroying the container based on the activation history.

27. The method as recited in claim **26**, wherein the predetermined duration is 100 ms.

28. The method as recited in claim **26**, wherein the method further comprises providing the plurality of warmed virtual machine instances before receiving the request.

29. The method as recited in claim **26**, wherein the software component comprises at least one of a runtime or one or more libraries.

30. The method as recited in claim **26**, further comprising:

determining, based on the activation history, that the identified virtual machine instance has not been used to execute the user code for a time period greater than a threshold time period; and

dissociating the identified virtual machine instance from the user account.

31. The method as recited in claim **26**, wherein the identified virtual machine instance comprises the container prior to receiving the request.

32. The method as recited in claim **31**, wherein the container comprises the user code prior to receiving the request.

33. The method as recited in claim **31**, further comprising selecting the container based on resource requirements associated with the request.

34. The method as recited in claim **26**, further comprising creating the container on the virtual machine instance after receiving the request.

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